Demonstrating Advanced U-space Services for Urban Air Mobility in a Co-Simulation Environment

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***Abstract*—The present paper formalises the development of a co-simulation environment aimed at demonstrating a number of advanced U-space services for the Air Mobility Urban-Large Experimental Demonstrations (AMU-LED) project. The environment has a visionary build that addresses Urban Air Mobility (UAM) challenges to support the High/Standard Performance Vehicles (HPV/SPV) operations within a complex urban environment by proposing an integrated solution that packages advanced services from the pre-flight to the in-flight phase in line with ongoing UAM Concept of Operations (ConOps). This setup opts for a holistic approach by promoting intelligent algorithmic design, artificial intelligence, robust serviceability through either virtual and live elements, and strong cooperation between the different services integrated, in addition to sustain interoperability with external U-space Service providers (USSP), Common Information Service providers (CISPs), and Air Traffic Controllers. The prototype has been recently showcased through the AMU-LED Cranfield (UK) demonstration activities.**

I. Introduction

The advent of Advanced Air Mobility (AAM) ecosystem takes part of smart cities development [1] and provides a preliminary view of what their airspace aspire: connected, safer and greener with a pared down road traffic. The global trends revolutionise the air transportation by extending traditional manned aviation and on-going development of unmanned traffic management (UTM) with new rules and regulations in urban areas characterised by the Urban Air Mobility (UAM) concepts [2]. The speculated ConOps intend to be challenged and tested with innovative operational scenarios in order to assess their feasibility. The current transition period for AAM is spreading its ambitious reform within the next decade by discussing, designing and validating these ConOps in the US through a joined initiative from FAA and NASA [3], in Australia supported by EmbraerX and airservices [4], in the UK under the umbrella of the Future Flight Challenges [5], and in EU through the U-space programmes led by SESAR [6]. This UAM emergence is determined by a significant progress coupling both technologies and manufacture development [7] that consider: battery performance, artificial intelligence (AI), electric propulsion, telemetry & 5G communication, and new navigation techniques, among others. In addition to the technology factor, UAM shall respond to a diversified demand [8]: air commute services, cargo, delivery, medical, logistics and even more use cases. It also values social acceptance [9] with public survey and through thoughtful infrastructures implementation that shall minimise the noise and privacy nuisances besides devoting efforts to deliver an inclusive transportation [10].

One of the key elements within those ConOps is the Services, which are intended to support the operators to enable safe and efficient use of the airspace volumes via meeting operational requirements and in compliance with regulatory requirements. Within recent research and development activities, the services and relevant supporting technologies have been widely studied, for instances: In PODIUM [11], the project tested the performance of pre-flight and in-flight services using different scenarios ranging from airport locations to beyond visual line of sight. The results were used to draw up recommendations on future deployment, regulations and standards. In SAFIR [12], the objective of this project is to test several U-space services managed by three U-space Service Providers (USSP) and one Air Navigation Service Provider (ANSP) within a real urban environment. The USIS [13] project sought to validate the services that will be provided by USSP to drone operators and third parties, including the authorities in charge of the airspace, to demonstrate their readiness at a European level. The study considered initial U-space services as well as more advanced services necessary for beyond visual line of sight and operations over people and resulted for the U1/U2 services into categories. In DOMUS [14], by integrating the already developed technologies and concepts under a centralised architecture, the study showed that the initial and some advanced U-space services, including tactical de-confliction, are feasible. The IMPETUS [15] project looked at what information is needed and how it will be used by drones in very low-level airspace. An information management architecture based on micro-services is proposed, which supports the testing of various U-space services.

Flight demonstration is an effective means to verify the operational capabilities of the overall system in specific environments and the maturity of services and technologies,

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contributing to conceptual validation and implementation. In addition to real-flight demonstration, simulation is also a key enabler of the development, which allows researchers to explore and evaluate concepts, techniques, services and architectures that are still being defined yet will serve as critical foundations for the future proof of concepts. In recent years, a growing body of research has shown the capability in providing a holistic simulation framework. As one of the early efforts, NASA, in collaboration with various stakeholders, has developed a multi-faceted simulation component hosted in its UTM Laboratory, which supports near-term live flight testing in addition to further term concept exploration. Fe3, a fast-time simulation tool developed by NASA has been used to study the high-density and low-altitude air traffic system. It is composed of two key functions: trajectory generation and collision avoidance, which has proved the capability of performing high-fidelity Monte Carlo simulations to support statistical analysis of the UTM operation [16]. In the scope of project METROPOLIS [17], the Traffic Manager (TMX) software was used as the simulation platform which is based on a medium-fidelity desktop simulation application designed for the investigation of novel ATM concepts. The advances in agent-based techniques have enhanced the simulation of UTM operation scenarios where constant coordination with stakeholders is envisioned. A survey has been conducted across a number of well-known agent-based frameworks, such as Gazebo, AirSim and Janus, comparing their applications in UTM simulations [18].

This paper focuses on demonstrating a series of advanced U-Space services as a whole for AMU-LED ConOps validation through the Cranfield (UK) demonstration [19]. The term of "advanced" envisions how the UAM may further evolve in the future: innovative methodologies beyond the state-of-the-art being reflected in the novelty of the services proposed. The main contributions involve building up a co-simulation environment that mimics and supports UAM operations with a high level of automation considering the co-existence of both virtual and live elements; and assessing the effects of the advanced services through a holistic approach. The co-simulation environment integrates a set of virtual U-space services, as a result of our previous and ongoing research activities, encompassing operation plan optimisation [20], risk analysis assistance [21], dynamic capacity management [22] and strategic conflict resolution [23] for the pre-flight phase. On the other hand, conformance monitoring [24], contingency management [25], and tactical conflict resolution [26], as well as a basic collaborative interface with ATC, are connected for the in-flight phase of demonstration.

II. Integration Framework

This section presents an overview of the co-simulation environment characterised by three main parts: the pre-flight services block, the flight plan compiler, and the in-flight services block. A high-level diagram of the architecture is introduced, illustrating the main interactions within these components.

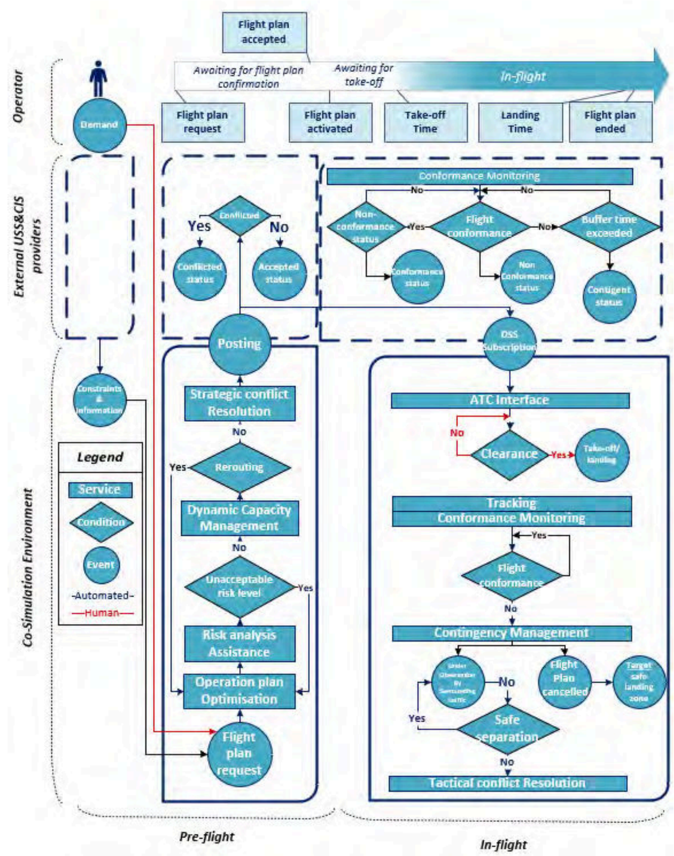


Figure 1. Services integration framework.

A. Pre-flight services block

Assuming an operator plans a flight in a designated airspace, the operation plan optimisation service embedded with the risk analysis assistance service (see Sec. III-A and Sec. III-B) can support to propose a route in quest of the best trade-off between safeness and route relevant costs. However, such route shall meet the demand-capacity balancing requirement confirmed by the dynamic capacity management service (see Sec. III-C). To this end, the flight plan is segmented into waypoints referred to as a 4-dimensional trajectory: latitude, longitude, altitude and time, which is used to map the predicted traffic demand against the airspace capacity.

The generated flight plan is materialised in a form containing the following information: (1) Operator information: its identity and its volume according to its performance (see Sec. V-A); (2) Waypoint coordinates: Latitude, Longitude, Altitude above ground level (AGL), Altitude regarding the WGS-84 reference, Epoch time.

Then, the strategic conflict resolution service (see III-D) calls the flight plan into question by analysing if it intersects with another active operation. This is performed after the trajectory is first extended with the operational volume concept. If any conflict exists, the operator is informed and needs to process the previous planning again until receiving a confirmation.

B. Flight plan compiler

After validating from the pre-flight services described in II-A, the flight plans need to be processed internally. The integrated in-flight services will be hosted on a simulator (i.e., BlueSky [27]), which requires converting the stored flight plans into comprehensible data.

A compiler aims to extract simulation information and connect the pre-flight block (Sec. II-A) and in-flight block (Sec. II-C). As presented in Figure 2, it has the following main tasks: (1) Extraction: As multiple operations can be submitted within a short period, the stored database may contain several operations that need to be parsed by the compiler into independent flight plans; (2) Read: Each flight plan corresponds to a unique operation, and this includes a set of waypoints that contains the information to enable the flight conformance monitoring; (3) Assignation: Flight plans are converted into objects that will be accessible by the in-flight services (See. II-C); (4) Generation: Initialise the position of the operator in the simulator, and schedule its take-off time and instructions until the end of the operation; (5) Save: The database read by the compiler will be moved into a long-term repository to record the operation history. The compiler will process from (1) to (5) in a loop in a high frequency to profit from high reactivity between flight plan submission and generation.

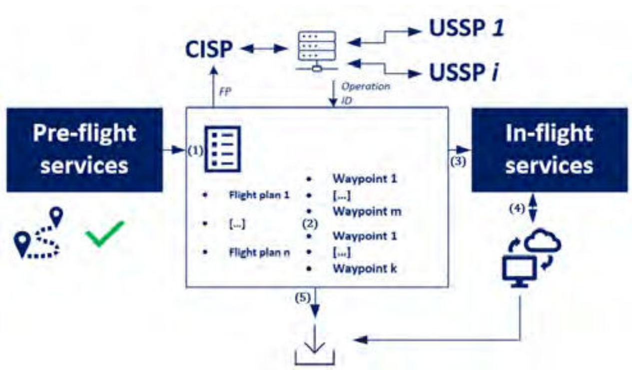


Figure 2. Flight plan compiler tasks workflow.

C. In-flight services block

When closer to the planned take-off time, an operation status switches from "accepted" to "activated" and a smooth tracking begins: the status remains activated as long as the flight is conforming. In the event where a flight is no longer conforming, a "non-conformance" status is notified, which may be switched to "contingent" status if it persists for a certain period of time (see Sec. IV-A).

If a contingent event occurs, the contingency protocol (see Sec. IV-B) is triggered. Consequently, the submitted flight plan becomes obsolete and the surrounding traffic is no longer safe in their conformance volume, leading to the tactical conflict resolution service (see Sec. IV-C) that allows to detect and protect the traffic from hazardous with the contingent operator. Finally, an operation is withdrawn from the co-simulation environment when the operation reaches its destination.

III. Pre-flight services

This section details the integrated simulation modules aimed at supplying pre-flight services, starting from original operation demands to eventually conflict-free flight plans, which mainly involve operation plan optimisation, risk analysis assistance, dynamic capacity management and strategic conflict resolution.

A. Operation plan optimisation

A 3D airspace model is first built to represent the demonstration environment. This airspace is discretised into a set of volumes of the same dimension. Each volume is connected to its adjacent in 10 directions (8 for horizontal and 2 for up and down) except for those crossing the airspace constraints or on the boundary. In addition, altitude layers are added to the associated volumes to reflect the vertical operation. Based on the airspace model, environmental data including terrain and constraints information is considered, where the constraints mainly cover tall buildings and power stations, airport obstacles as well as high population density areas.

This service offers operational plan generation assistance. After receiving the flight requests containing the coordinates of the starting and ending point, a commonly-used A* algorithm is applied to search the shortest path composed of a set of sequential airspace volumes. The trajectory consists of 3 parts which are vertical take-off and landing, as well as the cruise phase. It is assumed that the cruise phase follows the climb phase after the UAS reaches the top of the climb point, and precedes the landing phase. An illustrative example of the generated trajectories is shown in Figure 3: the curved path segments are formed when the trajectories bypassing the high-risk or constraint areas during the process.

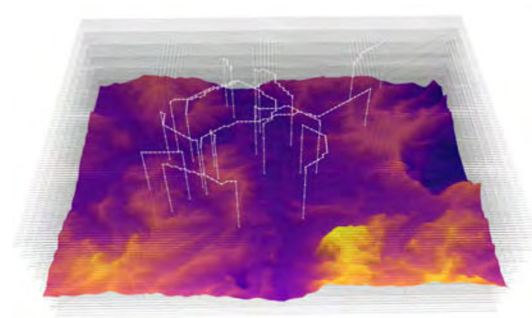


Figure 3. Generated trajectories in the designated airspace.

In addition to generating the original flight plans, this module will interact with others to optimise the trajectory until the potential risks are mitigated as reminded in Figure 1. With the interface between this module and the risk analysis (see Sec. III-B), if an unacceptable risk is returned, specific obstacle circles raising the high-risk areas traversed by the flight path will be returned to the operation plan optimisation service. Then, the trajectories will be fine-tuned there based on the feedback and will be sent back to the risk analysis module to check if the risk has been resolved or if a new threat occurs. This process is repeated until the risk level for all flight segments is acceptable.

B. Risk analysis assistance

The risk analysis service performs a qualitative and quantitative risk assessment of flight plans to ensure the operation safeness within the mission area. The general workflow of the module's operation is shown in Figure 4.

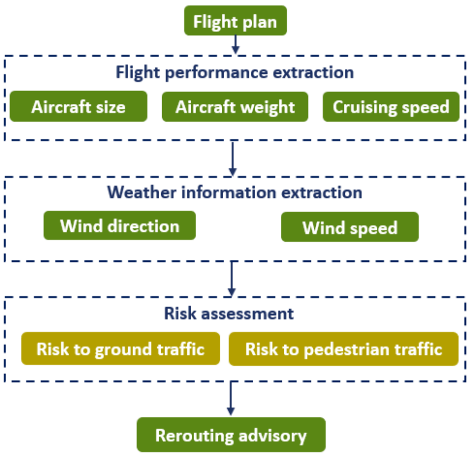


Figure 4. Flight plan risk assessment process.

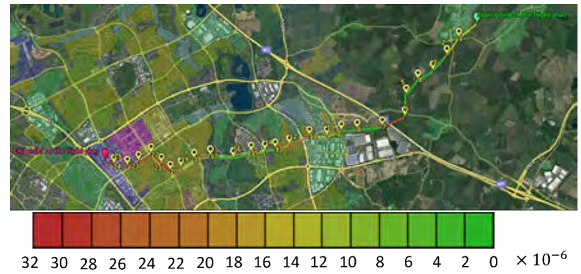
Before the validation and activation, the flight plan requested by an operator shall firstly be filtered from any risks related to ground traffic or pedestrians. The value of the risk is compared against the actual quantitative safety targets for operations in urban areas, and therefore serves as a threshold benchmark. If the risk value exceeds this threshold, a low-risk optimisation of the flight plan (see Sec. III-A) is called back for trajectory modification to ensure mission safety.

As shown in Figure 4, after obtaining the flight plan, this service conducts its risk assessment combining aircraft performance and environmental factors. Basically the flight plan is interpreted as a series of trajectory segments bounded by waypoints. A specific colour is assigned for each severity of risk and applied for specific segment in Figure 5. From the analysis results Fig 5a, it can be seen that when the flight crosses highway or crowded ground area, the risk value of these segments is high.

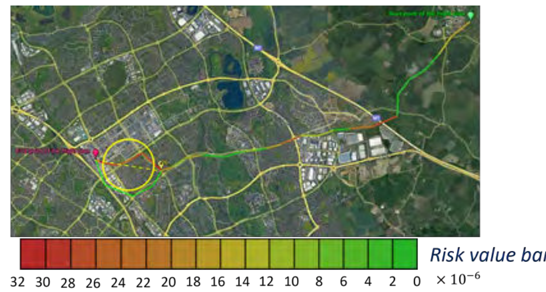
After obtaining the risk cost value for respective portion of the flight plan, it is compared with the risk threshold to filter out the high-risk segments of the proposed operation flight plan and provide suggestions for modification. As shown in Figure 5b, the flight plan has a high risk along the red routes and segregated (yellow circle), and therefore the operation plan optimisation algorithm generates an alternative path around the high-risk area.

C. Dynamic capacity management

The dynamic capacity management service aims to monitor the demand in airspace according to the activated flight plans



(a) Flight plan risk assessment.



(b) Flight plan modification.

Figure 5. Risk assessment based flight plan optimisation.

and regulates its access if a portion of that airspace is expected to reach its capacity limits. In this service, three different threads are involved: capacity, demand, and demand-capacity balancing (DCB).

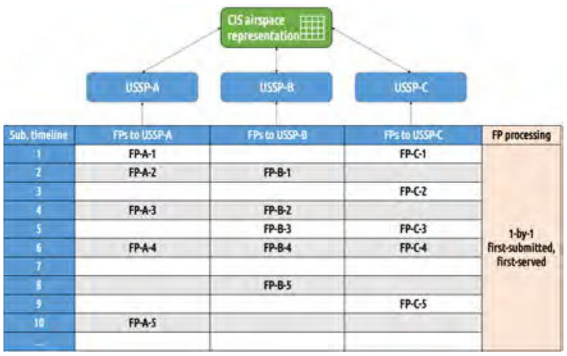
The capacity thread estimates the maximum number of operations that a piece of airspace can accommodate. Learning from conventional manned aviation, a grid-based partition is applied to the airspace to divide it into cells. The demand thread calculates the traffic demand for each sector based on the previously produced flight plans. Based on the airspace configuration (capacity thread), the trajectories (demand thread) are included, and the intersection between trajectories and airspace can be derived. Assuming any portion of the airspace becomes full, therefore turning into a hotspot, the flight can route away from that particular airspace. Alternative trajectory options that bypass each of the associated cells (except for the first and last ones for take-off and landing) will be generated using the same method in Sec. III-A. This is realised by turning off some specific airspace cells which contain grids passing through by the flight to prohibit a trajectory from entering into it during the path-finding process.

Given the input from both the capacity and the demand, a DCM model which computes and selects the optimal trajectory option is utilised to balance the demand and capacity. A detailed description of this approach is introduced in [22]. As a result, an optimal alternative option will be chosen as the rerouting path which will help reduce the load of the congested airspace.

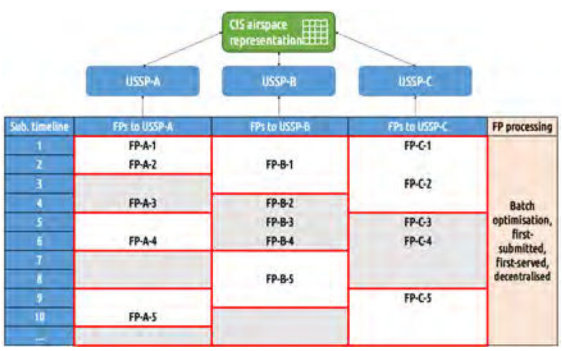
D. Strategic conflict resolution

The strategic conflict resolution (SCR) service focuses on detecting and resolving conflicts according to the flight plans at the pre-flight phase. It is usually referred to as the initiative that can help significantly reduce the need of tactical deconfliction and collision avoidance.

By sharing with relevant parties, the flight plans will be compared with the activated ones to examine if there is any conflict. If a conflict is identified, then a tentative change of the plan is proposed by means of delaying the take-off time for specific flights based on First-Come, First-Served (FCFS), see Figure 6a or global optimum principle, see Figure 6b, potentially followed by an iterative negotiation and re-submission process until there are no predicted conflicts. Intuitively, the service provider gets the information of airspace occupancy status and checks if any delay is required for the conflictual flight.



(a) FCFS rule.



(b) Global optimisation.

Figure 6. Two approaches for processing flight plans through the strategic conflict resolution service.

If a flight plan does not incur any conflicts, it can be activated and used to update the common airspace representation. This can be done in parallel as far as plenty of service providers can be involved handling their respective flight plans. Once a group of volumes (belonging to an activated flight) have been occupied for a requested period, they will not be available for the subsequent flight plans during that period until the current operation is ended. The detailed description about this approach can be found in [23].

IV. In-flight services

The in-flight services ensure a continuous monitoring of flight conformance of the active operations and provide decision-making support to prevent loss of separation or other unsafe circumstances. This section describes how this process is carried out from the previously generated flight plans.

A. Conformance monitoring

The conformance monitoring service in U-space ensures the detection of any flight deviation from their designated volume which might compromise their safety and operational efficiency as well as that of the surrounding traffic. The integrated conformance monitoring is embedded with a trajectory prediction function as shown with Figure 7 which zooms in the related part from the general framework Figure 1.

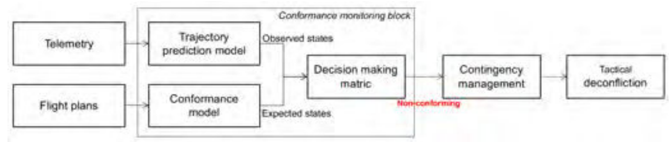


Figure 7. 4D flight plan conformance monitoring.

Firstly, the service is initiated by the previously generated flight plans: the simulator constructs a 4D trajectory-based volume along the waypoints assigned and therefore, delimits the conformance volume. After this initialisation, the service is fed by telemetry data throughout the operation to detect if their states subject to conformance verification. Continuously, the observed states extracted from our co-simulation environment is disseminated to an external system that simulates this telemetry information.

A short-term 4D trajectory prediction has been implemented to forecast minimal behaviour changes during flight considering tracking noise and weather effect on the trajectory. The conformance monitoring algorithm opts for a trajectory-based operation volume using overlapping polygon segments to build the operation intent volume. Another decisive variable of operation intent volume design is buffer sizing (i.e., tolerance) based on the vehicle performances (see Sec. V-A). For completeness of the monitoring service, keep-out Geo-fencing is also incorporated to represent the surrounding infrastructures and restricted areas as shown in Figure 8

Figure 8. Conformance monitoring interface.

The predicted trajectory based on current telemetry data for a flight should steadily fit with the operation intent volume. Hence, in the case of breaking the 4D volume boundaries, a non-conforming status is notified, being the colour of the specific flight highlighted. If such status continues for a certain period of time without prompt recovery, the services presented in the following sections are then triggered.

B. *Contingency management*

Contingency management plays a crucial role to provide very high level of safety, security, and efficiency to the system. Once the contingency situation is observed either by the operator or via an alert from the service provider, contingency actions take place to ensure safety for both the contingent vehicle and the whole surrounding traffic. The need of a system-wide contingency management concept and the base requirements for such a system is detailed in our previous work [25]. The contingency management steps demonstrated are depicted as in Figure 9.

Once the contingency manager block receives the contingent information, closest and feasible safe and emergency landing zones predefined by considering the risk assessment outputs, are calculated with certain margins with respect to the level of contingency. Afterwards, the closest and non-occupied option is selected as new destination point, selected landing zone is updated as being occupied in the database, and tactical deconfliction mode is under observation from the surrounding traffic point of view. The contingent vehicle is considered as a moving obstacle for the rest of the traffic. Finally, when the contingent vehicle lands safely, the selected safe/emergency landing zone status is updated back to non-occupied and the contingency manager block terminates.

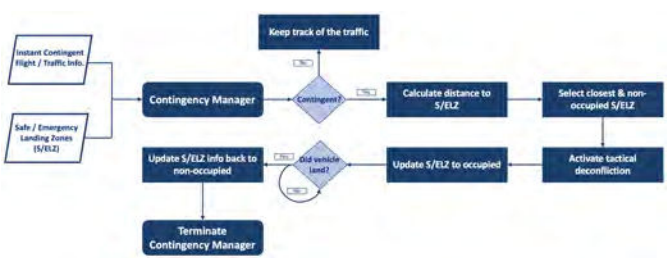


Figure 9. Contingency manager workflow.

The co-simulation environment deployment focuses on the emergency landing actions as contingency resolution and contingency identification is made depending on the flight conformance information. It is also assumed that the contingent vehicles were semi or fully controllable.

C. *Tactical conflict resolution*

The tactical conflict resolution service formalises another protection layer that prevents flights from a hazardous event where two UASs are no longer maintaining a safe separation. To meet the UAM challenges, the co-simulation environment proposes a reactive AI-based solution relying on a centralised multi-agent system: this mode takes over the control of the speed command when a safe separation is no longer respected:

- Observation layer: Each UAS observes the contingent operations within this area; the ownship receives the encoded information of this contingent operator. If no observation, the tactical mode sleeps. (Yellow circle - Figure 13)
- Conflicting layer: Assumed as the well clear boundary, this range declares a conflict, and therefore the UAS is fed by the centralised AI for speed action until the deconfliction. (Orange circle - Figure 13)

The flight command might be no longer available for contingent aircraft. Following this hypothesis, the tactical mode instruction is muted taking the priority to the surrounding traffic. Therefore, the traffic observing this event shall anticipate its behaviour, the centralisation of such a system has the benefit to solve multiple local conflicts simultaneously without human-in-the-loop.

The integrated multi-agent system is trained under a repetitive scenario that considers initial conditions uncertainties about the agents' performance model, the angle of the intersecting trajectory, the speed and the appearance flow in the observation range. Most of the scenario constraints have been ignored to design a flexible solution at the expense of tougher training due to poorer observation. The policy is informed by the local observation of the ownship: speed, acceleration, trajectory, and by the encoded data from the intruder: the relative angle of intersection, its performance model, the relative speed, the relative acceleration, and its relative separation (see [26] for more details).

D. *Collaborative interface with ATC*

A collaborative interface with ATC is required as unmanned operations might interact with manned aviation, especially around the airport. A general surveillance radar-like display has been used for creating such an interface. The purpose is to provide a global situational awareness into the co-simulation environment that couples the manned aviation traffic information with the unmanned in real-time for both live and virtual elements, as shown in Figure 10.

Figure 10. Live/virtual manned/unmanned traffic crossover.

We assume that telemetry will be used for the communication with UAS. For virtual vehicles, this tracking is purely with simulated signals. In the case of live vehicles, the simulator requests telemetry information from USSPs by specifying the operation IDs, which is streamed and injected to the simulator. On the other hand, the manned aviation traffic is reproduced by injecting ADS-B data from OpenSky Network (i.e., a platform that records historical and current global traffic information from ADS-B data).

Based on this situation awareness, this interface is supported by human-in-the-loop with both vocal and textual communications with concerned ATCs.

V. Experimental results

This section details the experimentation for demonstrating the above-mentioned U-space services with various scenarios using our developed co-simulation environment. The scenario setup is first introduced, followed by an analysis of experimental results derived from the pre-flight and in-flight services blocks.

A. Scenario setup

The co-simulation part of the AMU-LED UK demonstration showcases an one-hour run taking place over Cranfield, Milton Keynes and Bedford [10]. Live operations are performed in scenarios I, II, and IV at Cranfield airport including a (virtual) High Performing Vehicle (HPV), and two live Standard Performing Vehicles (SPV) [6] as shown in Table I represented with green, red and blue paths respectively. A smooth transition is planned between the scenarios valuing both virtual and live vehicles' interactions in the co-simulation environment.

- Bedford: The in-flight services are challenged. The scenario shown in Figure 11 proposes two contingency events inducing two tactical conflict resolutions. The first conflict event considers a single agent and the second two simultaneous deconflictions.
- Milton Keynes: The aim of this scenario is to test use cases such as air commute shuttle, point-to-point delivery, and surveillance utilising HPV or SPV within high traffic density areas supported by integrated pre-flight services. It focused on demonstrating the services' capability of reducing the probability of collision and congestion, as well as mitigating the risk to the ground.

The initial setup of the co-simulation can be recalled from the pre-flight services in Sec. III. After the flight plan is activated (i.e., as a result of the pre-flight services process), the operator is displayed in our co-simulation environment 5 minutes before its take-off time awaiting the operation to start. Each operation is identified by:

- Registration number: label assigned to the pilot.
- Operation type: SPV or HPV
- Serial number: unique reference that provides the UAS activity and its performance.
- Vehicle ID: label assigned to the UAS.
- Boundaries related to the aircraft performance (i.e. volume buffer):
  - Take-off & Landing radius: radius that delimits a safe horizontal perimeter for take-off & landing phases.
  - Altitude buffer: vertical tolerance of altitude around the allocated altitude in-flight phase.
  - Expand factor: qualitative tolerance of the volume size that delimits a safe polygon area in flight phases.

The co-simulation environment is refreshed every second. The tactical conflict resolution method respects a range of $d_{detect} = 2$ Nm and a conflicting range that triggers the mode when two aircraft no longer respect their separation $d_{conflict} = 0.5$ Nm. In this eventuality, the AI proposes a discrete speed change in $\mathcal{A} = [-3, -1, 0, 1, 3]$ kts for each iteration frame. The SPVs are assigned with either a low or medium expend factor and a high one for HPVs. Each volume allocated for the respective operators stays restricted 2 hours long. The 4D trajectory prediction seen in Figure 7 is refreshed every 2 seconds.

B. Results analysis

This flight demonstration focused on showing the feasibility of advanced U-space services as a whole to support safe and efficient UAS operations, involving essential services from flight plan generation to real-time conflict detection and resolution. The result analysis is presented in two parts, namely the pre-flight and the in-flight phases.

1) Pre-flight phase: As introduced in Sec.III, conflict-free flight plans with acceptable risk level will be generated based on the flight requests with the support of the set of pre-flight services.

Taking 12 flight plans in the Milton Keynes scenario as an example, the process of flight generation and optimisation by multiple pre-flight services is shown in Figure 12 step by step. Firstly, flight requests were generated based on the demonstration mission. Figure 12a shows the flight plan generated by directly connecting the origin and destination points from the flight request. Then, flight requests were sent to the flight planning module. As depicted in Figure 12b, evident deviation can be found in the trajectories which bypass all major high-risk areas while flying the shortest path. After getting feedback from the risk analysis assistance service, as the red trajectories showed in Figure 12c, the flight segment which contains unacceptable ground risk will be further rerouted (compared with Figure 12b). Finally, the flights are coordinated by the DCM model and the SCR model, where the results are illustrated in Figure 12d. Specifically, the pair of yellow trajectories are delayed for 20 and 10 minutes respectively after being processed by the SCR model. The trajectory marked in green was assigned to its second alternative trajectory by the DCM model.

Services in the pre-flight phase play an important role for the downstream tactical operations, especially in tactical conflict detection and resolution. If the operation plan were submitted as originally planned, there would be 6 conflicts as a result of 12 flight plans, bringing the number of affected operations to 5. This would greatly increase the pressure to the tactical phase, resulting in more operational risks. As such, the aim of

TABLE I: Advanced U-space services demonstration matrix.

Features	Cranfield I	Bedford Scenario	Cranfield IV	Milton Keynes Scenario	Cranfield II
Operation Plan Optimisation				✓	
Risk Analysis Assistance				✓	
Dynamic Capacity Management				✓	
Strategic Conflict Resolution				✓	
Conformance Monitoring		✓		✓	
Contingency Management		✓			
Tactical Conflict Resolution		✓			
Collaborative ATC Interface	✓		✓		✓
					

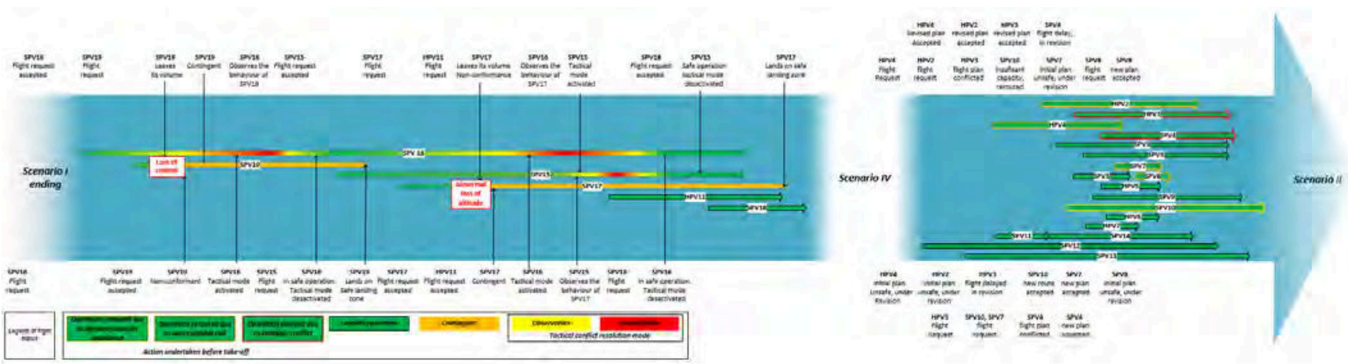
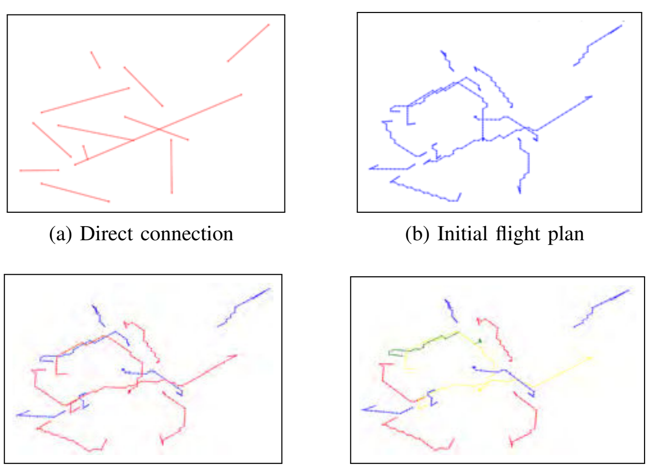


Figure 11. Detailed timeline of Bedford and Milton Keynes scenarios.



(a) Direct connection

(b) Initial flight plan

(c) After risk assessment

(d) After DCM and SCR

Figure 12. Flight plans processed by pre-flight services.

the pre-flight services is to build an early-stage safety net to protect the system from being overloaded.

2) In-flight phase: The ecosystem has proven a high robustness of in-flight tasks processing throughout the demonstration with fluent interoperability of services following Figure 13: The conformance volume delimited in blue ensures flight safety with a predictive tracking and high reactivity in case of violation. Surrounding traffic observes the contingency of SPV17 (orange icon): SPV16 (red icon) has no longer a safe separation and relies on the centralised AI for making decision while SPV15 firstly stays under observation (yellow icon) as long as the conflict edge (orange circle) is not violated by SPV17. This UAS pursues its prioritised emergency protocol (pink route): the power shortage requires an imminent landing to the nearest safety landing zone (highlighted by SLZ-033 or SPV17001). At the same time, HPV11 and SPV18 perform conform flights with close volumes but without hazards, in their location at the opposite side of the contingency, their tactical mode sleeps.

The Cranfield scenarios (I, II, and IV) have been demonstrated in a controlled airspace that challenges the service of collaborative interface with ATC. The link with the Cranfield's operational digital tower allowed a connection with our surveillance radar for human decision-making in a co-simulation environment where both live and virtual vehicles were operating at Cranfield Airport.

According to the information from the log file which recorded the data flow on the demonstration day, the distance between each flight pair at each time step (1 sec) is shown in Figure 14, where the total number of flight pairs is calculated by counting every possibilities. As can be seen from the the

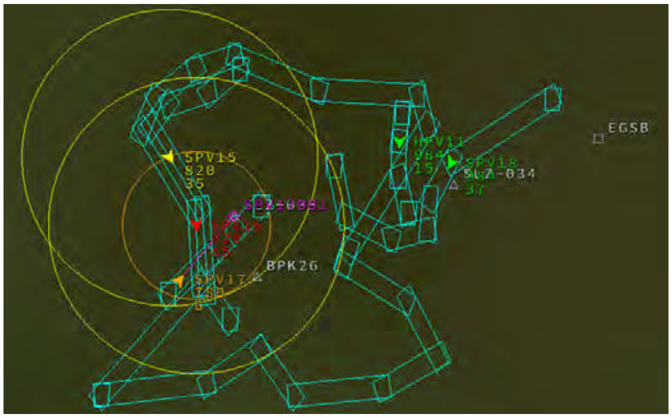


Figure 13. Multiple deconfliction case in Bedford scenario.

graph, in this high density operation scenario, most of the distances between flight pair are between 2.5 to 15.5 km which is a relatively safe distance for UAS operation. The effect of applying the advanced U-space services can be also seen from the distribution of those longer distance. It is worth noting that the number of times that the distance between aircraft pairs is less than 0.5 km is about 250. At the early stages of UAS operations, such distances can be considered as at risk of conflict. This is caused by the designed two contingency events and the close distance between the operating UAS and the landed UAS during a short period. In addition, the very long distances (e.g more than 70 km) is as a result of an air commute shuttle operation from Milton Keynes to London.

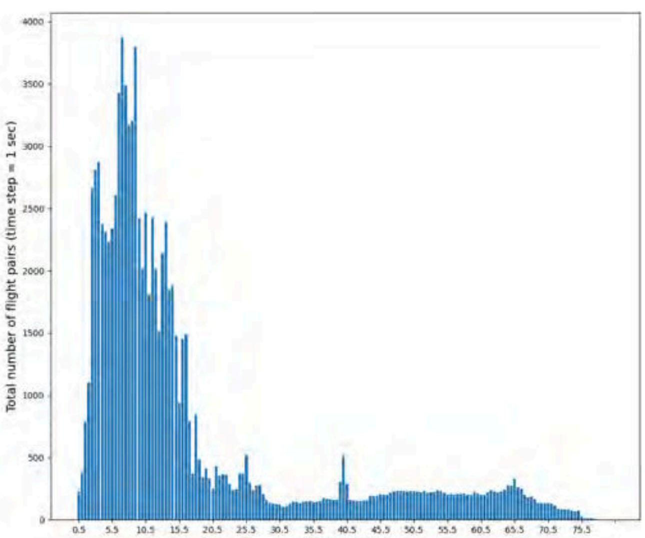


Figure 14. Distance dirtribution between each flight pair.

VI. Conclusions and further work

This paper presented a live/virtual constructive simulation environment that has been used to demonstrate 8 types of U-space services within the AMU-LED project. The developed services were grouped into two groups corresponding to the pre-flight and in-flight phase respectively. Within each group, the relevant services were integrated as an entire block, which in turn was bridged through a specifically devised flight plan compiler. These were demonstrated via five scenarios involving various use cases defined at Cranfield. Further development will be centred around improving the data models for the synthetic environment with higher fidelity; a modular design approach to allow easy plug-in of external service modules to the environment which could be deployed as a web-based application.

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